RANDOM ACCESS FOR WIRELESS MULTIPLE-ACCESS COMMUNICATION SYSTEMS

Claim of Priority under 35 U.S.C. §119

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 60/421,309, entitled "MIMO WLAN System," filed on October 25, 2002, assigned to the assignee of the present application, and incorporated herein by reference in its entirety for all purposes.

[0002] This application claims the benefit of U.S. Provisional Application Serial No. 60/432,440, entitled "Random Access For Wireless Multiple-Access Communication Systems," filed on December 10, 2002, assigned to the assignee of the present application, and incorporated herein by reference in its entirety for all purposes.

Reference to Co-Pending Applications for Patent

[0003] This application is further related to U.S. Provisional Application Serial No. No. 60/432,626, entitled "Data Detection and Demodulation for Wireless Communication Systems," filed on December 10, 2002, assigned to the assignee of the present application, and incorporated herein by reference in its entirety for all purposes.

BACKGROUND

[0004] The present invention relates generally to data communication, and more specifically to techniques for facilitating random access in wireless multiple-access communication systems.

Background

[0005] Wireless communication systems are widely deployed to provide various types of communication such as voice, packet data, and so on. These systems may be multiple-access systems capable of supporting communication with multiple user terminals by sharing the available system resources. Examples of such multiple-access systems include code division multiple access (CDMA) systems, time division multiple access (TDMA) systems, and frequency division multiple access (FDMA) systems.

[0006] In a multiple-access communication system, a number of user terminals may desire to gain access to the system at random times. These user terminals may or may not have registered with the system, may have timing that is skewed with respect to system timing, and may or may not know the propagation delays to their access points. Consequently, the transmissions from user terminals attempting to gain access to the system may occur at random times, and may or may not be properly time-aligned at a receiving access point. The access point would need to detect for these transmissions in order to identify the specific user terminals desiring to gain access to the system.

[0007] Various challenges are encountered in the design of a random access scheme for a wireless multiple-access system. For example, the random access scheme should allow user terminals to quickly gain access to the system with as few access attempts as possible. Moreover, the random access scheme should be efficient and consume as a little of the system resources as possible.

[0008] There is therefore a need in the art for an effective and efficient random access scheme for wireless multiple-access communication systems.

SUMMARY

[0009] Techniques are provided herein for facilitating random access in wireless multiple-access communication systems. In an aspect, a random access channel (RACH) is defined to comprise a "fast" random access channel (F-RACH) and a "slow" random access channel (S-RACH). The F-RACH and S-RACH are designed to efficiently support user terminals in different operating states and employ different designs. The F-RACH is efficient and can be used to quickly access the system, and the S-RACH is more robust and can support user terminals in various operating states and conditions. The F-RACH may be used by user terminals that have registered with the system and can compensate for their round trip delays (RTDs) by properly advancing their transmit timing. The S-RACH may be used by user terminals that may or may not have registered with the system, and may or may not be able to compensate for their RTDs. The user terminals may use the F-RACH or S-RACH, or both, to gain access to the system.

[0010] Various aspects and embodiments of the invention are described in further detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The features, nature, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. 1 shows a wireless multiple-access communication system;

FIG. 2 shows a time division duplexed (TDD) frame structure;

FIGS. 3A and 3B show slot structures for the F-RACH and S-RACH, respectively;

FIG. 4 shows an overall process for accessing the system using the F-RACH and/or S-RACH;

FIGS. 5 and 6 show processes for accessing the system using the F-RACH and S-RACH, respectively;

FIGS. 7A and 7B show exemplary transmissions on the S-RACH and F-RACH, respectively;

FIG. 8 shows an access point and two user terminals;

FIG. 9 shows a block diagram of a TX data processor at a terminal;

FIGS. 10A and 10B show block diagrams of the processing units within the TX data processor;

FIG. 11 shows a block diagram of a TX spatial processor within the terminal;

FIG. 12A shows a block diagram of an OFDM modulator; and

FIG. 12B illustrates an OFDM symbol.

DETAILED DESCRIPTION

[0012] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

[0013] FIG. 1 shows a wireless multiple-access communication system 100 that supports a number of users. System 100 includes a number of access points (APs) 110 that support communication for a number of user terminals (UTs) 120. For simplicity,

only two access points 110a and 110b are shown in FIG. 1. An access point is generally a fixed station that is used for communicating with the user terminals. An access point may also be referred to as a base station or some other terminology.

[0014] User terminals 120 may be dispersed throughout the system. Each user terminal may be a fixed or mobile terminal that can communicate with the access point. A user terminal may also be referred to as an access terminal, a mobile station, a remote station, a user equipment (UE), a wireless device, or some other terminology. Each user terminal may communicate with one or possibly multiple access points on the downlink and/or the uplink at any given moment. The downlink (i.e., forward link) refers to transmission from the access point to the user terminal, and the uplink (i.e., reverse link) refers to transmission from the user terminal to the access point.

[0015] In FIG. 1, access point 110a communicates with user terminals 120a through 120f, and access point 110b communicates with user terminals 120f through 120k. A system controller 130 couples to access points 110 and may be designed to perform a number of functions such as (1) coordination and control for the access points coupled to it, (2) routing of data among these access points, and (3) control of access and communication with the user terminals served by these access points.

[0016] The random access techniques described herein may be used for various wireless multiple-access communication systems. For example, these techniques may be used for systems that employ (1) one or multiple antennas for data transmission and one or multiple antennas for data reception, (2) various modulation techniques (e.g., CDMA, OFDM, and so on), and (3) one or multiple frequency bands for the downlink and uplink.

[0017] For clarity, the random access techniques are specifically described below for an exemplary wireless multiple-access system. In this system, each access point is equipped with multiple (e.g., four) antennas for data transmission and reception, and each user terminal may be equipped with one or multiple antennas.

[0018] The system further employs orthogonal frequency division multiplexing (OFDM), which effectively partitions the overall system bandwidth into a number of (NF) orthogonal subbands. In one specific design, the system bandwidth is 20 MHz, $N_F = 64$, the subbands are assigned indices of –32 to +31, the duration of each transformed symbol is 3.2 μsec, the cyclic prefix is 800 nsec, and the duration of each

OFDM symbol is 4.0 μsec. An OFDM symbol period, which is also referred to as a symbol period, corresponds to the duration of one OFDM symbol.

[0019] The system also uses a single frequency band for both the downlink and uplink, which share this common band using time-division duplexing (TDD). Moreover, the system employs a number of transport channels to facilitate data transmission on the downlink and uplink.

[0020] FIG. 2 shows a frame structure 200 that may be used for a wireless TDD multiple-access system. Transmissions occur in units of TDD frames, each of which covers a particular time duration (e.g., 2 msec). Each TDD frame is partitioned into a downlink phase and an uplink phase. Each of the downlink and uplink phases is further partitioned into multiple segments for multiple downlink/uplink transport channels.

[0021] In the embodiment shown in FIG. 2, the downlink transport channels include a broadcast channel (BCH), a forward control channel (FCCH), and a forward channel (FCH), which are transmitted in segments 210, 220, and 230, respectively. The BCH is used to send (1) a beacon pilot that may be used for system timing and frequency acquisition, (2) a MIMO pilot that may be used for channel estimation, and (3) a BCH message that carries system information. The FCCH is used to send acknowledgments for the RACH and assignments of downlink and uplink resources. The FCH is used to send user-specific data packets, page and broadcast messages, and so on, on the downlink to the user terminals.

[0022] In the embodiment shown in FIG. 2, the uplink transport channels include a reverse channel (RCH) and a random access channel (RACH), which are transmitted in segments 240 and 250, respectively. The RCH is used to send data packets on the uplink. The RACH is used by the user terminals to gain access to the system.

[0023] The frame structure and transport channels shown in FIG. 2 are described in further detail in the aforementioned provisional U.S. Patent Application Serial No. 60/421,309.

1. <u>RACH Structure</u>

[0024] In an aspect, the RACH is comprised of a "fast" random access channel (F-RACH) and a "slow" random access channel (S-RACH). The F-RACH and S-RACH are designed to efficiently support user terminals in different operating states and employ different designs. The F-RACH may be used by user terminals that have

registered with the system and can compensate for their round trip delays (RTDs) by properly advancing their transmit timing, as described below. The S-RACH may be used by user terminals that have acquired the system frequency (e.g., via the beacon pilot sent on the BCH) but may or may not have registered with the system. When transmitting on the S-RACH, the user terminals may or may not be compensating for their RTDs.

[0025] Table 1 summarizes the requirements and characteristics of the F-RACH and S-RACH.

Table 1

RACH Type	Description
F-RACH	Use for system access by user terminals that (1) have registered with the system, (2) can compensate for their round trip delay, and (3) can achieve the required received signal-to-noise ratio (SNR). A slotted Aloha random access scheme is used for the F-RACH.
S-RACH	Use for system access by user terminals that cannot use the F-RACH, e.g., because of failure to meet any of the requirements for using the F-RACH. An Aloha random access scheme is used for the S-RACH.

[0026] Different designs are used for the F-RACH and S-RACH to facilitate rapid access to the system whenever possible and to minimize the amount of system resources needed to implement random access. In an embodiment, the F-RACH uses a shorter protocol data unit (PDU), employs a weaker coding scheme, and requires F-RACH PDUs to arrive approximately time-aligned at the access point. In an embodiment, the S-RACH uses a longer PDU, employs a stronger coding scheme, and does not require S-RACH PDUs to arrive time-aligned at the access point. The designs of the F-RACH and S-RACH and their use are described in detail below.

[0027] In a typical wireless communication system, each user terminal aligns its timing to that of the system. This is normally achieved by receiving from an access point a transmission (e.g., the beacon pilot sent on the BCH) that carries or is embedded with timing information. The user terminal then sets its timing based on the received timing information. However, the user terminal timing is skewed (or delayed) with respect to the system timing, where the amount of skew typically corresponds to the propagation

delay for the transmission that contains the timing information. If the user terminal thereafter transmits using its timing, then the received transmission at the access point is effectively delayed by twice the propagation delay (i.e., the round trip delay), where one propagation delay is for the difference or skew between the user terminal timing and the system timing and the other propagation delay for the transmission from the user terminal to the access point (see FIG. 7A). For a transmission to arrive at a specific time instant based on the access point timing, the user terminal would need to adjust its transmit timing to compensate for the round trip delay to the access point (see FIG. 7B).

[0028] As used herein, an RTD compensated transmission refers to a transmission that has been sent in a manner such that it arrives at a receiver at a designated time instant based on the receiver timing. (There can be some errors, so the transmission may be received close to, and not necessarily exactly at, the designated time instant.) If the user terminal is able to align its timing to that of the system (e.g., the timing for both is obtained based on GPS time), then an RTD compensated transmission would only need to account for the propagation delay from the user terminal to the access point.

[0029] FIG. 2 also shows an embodiment of a structure for the RACH. In this embodiment, RACH segment 250 is partitioned into three segments: a segment 252 for the F-RACH, a segment 254 for the S-RACH, and a guard segment 256. The F-RACH segment is first in the RACH segment because transmissions on the F-RACH are RTD compensated and would therefore not interfere with transmissions in the preceding RCH segment. The S-RACH segment is next in the RACH segment because transmissions on the S-RACH may not be RTD compensated and may interfere with those in the preceding RCH segment if placed first. The guard segment follows the S-RACH segment and is used to prevent S-RACH transmissions from interfering with the downlink transmission for the BCH in the next TDD frame.

[0030] In an embodiment, the configuration of both the F-RACH and S-RACH can be dynamically defined by the system for each TDD frame. For example, the starting location of the RACH segment, the duration of the F-RACH segment, the duration of the S-RACH segment, and the guard interval may be individually defined for each TDD frame. The duration of the F-RACH and S-RACH segments may be selected based on various factors such as, for example, the number of registered/unregistered user terminals, system loading, and so on. The parameters conveying the F-RACH and S-

RACH configuration for each TDD frame may be sent to the user terminals via the BCH message that is transmitted in the same TDD frame.

[0031] FIG. 3A shows an embodiment of a slot structure 300 that may be used for the F-RACH. The F-RACH segment is partitioned into a number of F-RACH slots. The specific number of F-RACH slots available in each TDD frame is a configurable parameter that is conveyed in the BCH message sent in the same TDD frame. In an embodiment, each F-RACH slot has a fixed duration that is defined to be equal to, for example, one OFDM symbol period.

[0032] In an embodiment, one F-RACH PDU may be sent in each F-RACH slot. The F-RACH PDU comprises a reference portion that is multiplexed with an F-RACH message. The F-RACH reference portion includes a set of pilot symbols that is transmitted on one set of subbands, and the F-RACH message comprises a group of data symbols that is transmitted on another set of subbands. The pilot symbols may be used for channel estimation and data demodulation. The subband multiplexing, processing for the F-RACH PDU, and operation of the F-RACH for system access are described in further detail below.

[0033] Table 2 lists the fields for an exemplary F-RACH message format.

Table 2 - F-RACH Message

Fields Names	**Length (bits)**	**Description**
MAC ID	10	Temporary ID assigned to user terminal
Tail Bits	6	Tail bits for convolutional encoder

[0034] The medium access control (MAC) ID field contains the MAC ID that identifies the specific user terminal sending the F-RACH message. Each user terminal registers with the system at the start of a communication session and is assigned a unique MAC ID. This MAC ID is thereafter used to identify the user terminal during the session. The Tail Bits field includes a group of zeros used to reset a convolutional encoder to a known state at the end of the F-RACH message.

[0035] FIG. 3B shows an embodiment of a slot structure 310 that may be used for the S-RACH. The S-RACH segment is also partitioned into a number of S-RACH slots. The specific number of S-RACH slots available for use in each TDD frame is a

configurable parameter that is conveyed in the BCH message transmitted in the same TDD frame. In an embodiment, each S-RACH slot has a fixed duration that is defined to be equal to, for example, four OFDM symbol periods.

[0036] In an embodiment, one S-RACH PDU may be sent in each S-RACH slot. The S-RACH PDU comprises a reference portion followed by an S-RACH message. In a specific embodiment, the reference portion includes two pilot OFDM symbols that are used to facilitate acquisition and detection of the S-RACH transmission as well as to aid in coherent demodulation of the S-RACH message portion. The pilot OFDM symbols may be generated as described below.

[0037] Table 3 lists the fields for an exemplary S-RACH message format.

Table 3 - S-RACH Message

Fields Names	Length (bits)	Description
MAC ID	10	Temporary ID assigned to user terminal
CRC	8	CRC value for the S-RACH message
Tail Bits	6	Tail bits for convolutional encoder

[0038] For the embodiment shown in Table 3, the S-RACH message includes three fields. The MAC ID and Tail Bits fields are described above. The S-RACH may be used by unregistered user terminals for system access. For the first system access by an unregistered user terminal, a unique MAC ID has not yet been assigned to the user terminal. In this case, a registration MAC ID that is reserved for registration purpose may be used by the unregistered user terminal until a unique MAC ID is assigned. The registration MAC ID is a specific value (e.g., 0x0001). The cyclic redundancy check (CRC) field contains a CRC value for the S-RACH message. This CRC value may be used by the access point to determine whether the received S-RACH message is decoded correctly or in error. The CRC value is thus used to minimize the likelihood of incorrectly detecting the S-RACH message.

[0039] Tables 2 and 3 show specific embodiments of the formats for the F-RACH and S-RACH messages. Other formats with fewer, additional, and/or different fields may also be defined for these messages, and this is within the scope of the invention. For example, the S-RACH message may be defined to include a Slot ID field that carries the

index of the specific S-RACH slot in which the S-RACH PDU was sent. As another example, the F-RACH message may be defined to include a CRC field.

[0040] FIGS. 3A and 3B show specific structures for the F-RACH and S-RACH. Other structures may also be defined for the F-RACH and S-RACH, and this is within the scope of the invention. For example, the F-RACH and/or S-RACH may be defined to have configurable slot duration, which may be conveyed in the BCH message.

[0041] FIGS. 3A and 3B also show specific embodiments of the F-RACH and S-RACH PDUs. Other PDU formats may also be defined, and this is also within the scope of the invention. For example, subband multiplexing may also be used for the S-RACH PDU. Moreover, the portions of each PDU may be defined with sizes that are different from those described above. For example, the reference portion of the S-RACH PDU may be defined to include only one pilot OFDM symbol.

[0042] The use of the F-RACH and S-RACH for random access can provide various benefits. First, improved efficiency is achieved by segregating user terminals into two groups. User terminals that can meet timing and received SNR requirements can use the more efficient F-RACH for random access, and all other user terminals can be supported by the S-RACH. The F-RACH can be operated as a slotted Aloha channel, which is known to be approximately two times more efficient than an unslotted Aloha channel. User terminals that cannot compensate for their RTDs would be restricted to the S-RACH and would not interfere with user terminals on the F-RACH.

[0043] Second, different detection thresholds may be used for the F-RACH and S-RACH. This flexibility allows the system to achieve different goals. For example, the detection threshold for the F-RACH may be set higher than the detection threshold for the S-RACH. This would then allow the system to favor user terminals that are more efficient (i.e., with higher received SNRs) to access the system via the F-RACH, which may provide higher overall system throughput. The detection threshold for the S-RACH may be set lower to allow all user terminals (with a particular minimum received SNR) to access the system.

[0044] Third, different designs and PDUs may be used for the F-RACH and S-RACH. For the specific embodiments described above, the F-RACH PDU comprises one OFDM symbol and the S-RACH PDU comprises four OFDM symbols. The different PDU sizes are due to different data being sent by the users of the F-RACH and users of the S-RACH and also due to different coding schemes and required received SNRs for

the F-RACH and S-RACH. Overall, the F-RACH would then be approximately eight times more efficient than the S-RACH, where a factor of four comes from the shorter PDU size and a factor of two comes from the slotted nature of the F-RACH. Thus, for the same segment duration, the F-RACH can support eight times the number of user terminals that the S-RACH can support. Viewed another way, the same number of user terminals can be supported by an F-RACH segment that is 1/8 the duration of the S-RACH segment.

2. Random Access Procedures

[0045] The user terminals may use the F-RACH or S-RACH, or both, to gain access to the system. Initially, user terminals that have not registered with the system (i.e., those that have not been assigned unique MAC IDs) use the S-RACH to access the system. Once registered, the user terminals may use the F-RACH and/or S-RACH for system access.

[0046] Because different designs are used for the F-RACH and S-RACH, successful detection of a transmission on the F-RACH requires a higher received SNR than that required for a transmission on the S-RACH. For this reason, a user terminal that cannot transmit at a sufficient power level to achieve the required received SNR for the F-RACH can default to using the S-RACH. Moreover, if a user terminal fails to access the system after a specified number of consecutive attempts on the F-RACH, then it can also default to using the S-RACH.

[0047] FIG. 4 shows a flow diagram of an embodiment of a process 400 performed by a user terminal for accessing the system using the F-RACH and/or S-RACH. Initially, a determination is made whether or not the user terminal has registered with the system (step 412). If the answer is no, then the S-RACH is used for system access and the process proceeds to step 430. Otherwise, a determination is next made whether or not the received SNR achieved for the user terminal is greater than or equal to the required received SNR for the F-RACH (i.e., the F-RACH threshold SNR) (step 414). Step 414 may be skipped if the received SNR for the user terminal is not known. If the answer for step 414 is no, then the process also proceeds to step 430.

[0048] If the user terminal is registered and the F-RACH threshold SNR is met, then an F-RACH access procedure is performed to attempt to access the system (step 420). After completion of the F-RACH access procedure (an embodiment of which is

described below in FIG. 5), a determination is made whether or not access was successful (step 422). If the answer is yes, then access success is declared (step 424) and the process terminates. Otherwise, the process proceeds to step 430 to attempt access via the S-RACH.

[0049] If the terminal is not registered, cannot achieve the F-RACH threshold SNR, or was unsuccessful in gaining access via the F-RACH, then it performs an S-RACH access procedure to attempt to access the system (step 430). After completion of the S-RACH access procedure (an embodiment of which is described below in FIG. 6), a determination is made whether or not access was successful (step 432). If the answer is yes, then access success is declared (step 424). Otherwise, access failure is declared (step 434). In either case, the process then terminates.

[0050] For simplicity, the embodiment shown in FIG. 4 assumes that the user terminal has up-to-date RTD information if it is registered with the system. This assumption is generally true if the user terminal is stationary (i.e., at a fixed location) or if the wireless channel has not changed appreciably. For a mobile user terminal, the RTD may change noticeably between system accesses, or maybe even from access attempt to access attempt. Thus, process 400 may be modified to include a step to determine whether or not the user terminal has up-to-date RTD information. This determination may be made based on, for example, the elapsed time since the last system access, the observed channel behavior during the last system access, and so on.

[0051] In general, multiple types of random access channels are available, and one random access channel is selected for use initially based on the operating state of the user terminal. The operating state may be defined, for example, by the registration status of the user terminal, the received SNR, current RTD information, and so on. The user terminal may use multiple random access channels, one channel at a time, for system access.

A. <u>F-RACH Procedure</u>

[0052] In an embodiment, the F-RACH uses a slotted Aloha random access scheme whereby user terminals transmit in randomly selected F-RACH slots to attempt to gain access to the system. The user terminals are assumed to have current RTD information when transmitting on the F-RACH. As a result, the F-RACH PDUs are assumed to be time-aligned to F-RACH slot boundaries at the access point. This can greatly simplify

the detection process and shorten the access time for user terminals that can meet the requirements for using the F-RACH.

[0053] A user terminal may send multiple transmissions on the F-RACH until access is gained or the maximum permitted number of access attempts has been exceeded. Various parameters may be changed for each F-RACH transmission to improve the likelihood of success, as described below.

[0054] **FIG. 5** shows a flow diagram of an embodiment of a process 420a performed by the user terminal for accessing the system using the F-RACH. Process 420a is an embodiment of the F-RACH access procedure performed in step 420 in FIG. 4.

[0055] Prior to the first transmission on the F-RACH, the user terminal initializes various parameters used for transmissions on the F-RACH (step 512). Such parameters may include, for example, the number of access attempts, the initial transmit power, and so on. A counter may be maintained to count the number of access attempts, and this counter may be initialized to one for the first access attempt. The initial transmit power is set such that the required received SNR for the F-RACH can be expected to be achieved at the access point. The initial transmit power may be estimated based on the received signal strength or SNR for the access point, as measured at the user terminal. The process then enters a loop 520.

[0056] For each transmission on the F-RACH, the user terminal processes the BCH to obtain pertinent system parameters for the current TDD frame (step 522). As described above, the number of F-RACH slots available in each TDD frame and the start of the F-RACH segment are configurable parameters that can change from frame to frame. The F-RACH parameters for the current TDD frame are obtained from the BCH message that is sent in the same frame. The user terminal then randomly selects one of the available F-RACH slots to transmit an F-RACH PDU to the access point (step 524). The user terminal then transmits the F-RACH PDU with compensation for the RTD such that the PDU arrives approximately time-aligned to the start of the selected F-RACH slot at the access point (step 526).

[0057] The access point receives and processes the F-RACH PDU, recovers the encapsulated F-RACH message, and determines the MAC ID included in the recovered message. For the embodiment shown in Table 2, the F-RACH message does not include a CRC value, so the access point is not able to determine whether the message was decoded correctly or in error. However, since only registered user terminals use the

F-RACH for system access and since each registered user terminal is assigned a unique MAC ID, the access point can check the received MAC ID against the assigned MAC IDs. If the received MAC ID is one of the assigned MAC IDs, then the access point acknowledges receipt of the received F-RACH PDU. This acknowledgment may be sent in various manners, as described below.

[0058] After transmitting the F-RACH PDU, the user terminal determines whether or not an acknowledgment has been received for the transmitted PDU (step 528). If the answer is yes, then the user terminal transitions to an Active state (step 530), and the process terminates. Otherwise, if an acknowledgement is not received for the transmitted F-RACH PDU within a specified number of TDD frames, then the user terminal assumes that the access point did not receive the F-RACH PDU and resumes the access procedure on the F-RACH.

[0059] For each subsequent access attempt, the user terminal first updates the F-RACH transmission parameters (step 534). The updating may entail (1) incrementing the counter by one for each subsequent access attempt and (2) adjusting the transmit power (e.g., increasing it by a particular amount). A determination is then made whether or not the maximum permitted number of access attempts on the F-RACH has been exceeded based on the updated counter value (step 536). If the answer is yes, then the user terminal remains in an Access state (step 538), and the process terminates.

[0060] If the maximum permitted number of access attempts has not been exceeded, then the user terminal determines the amount of time to wait before transmitting the F-RACH PDU for the next access attempt. To determine this wait time, the user terminal first determines the maximum amount of time to wait for the next access attempt, which is also referred to as the contention window (CW). In an embodiment, the contention window (which is given in units of TDD frames) exponentially increases for each access attempt (i.e., $CW = 2^{access\_attempt}$). The contention window may also be determined based on some other function (e.g., a linear function) of the number of access attempts. The amount of time to wait for the next access attempt is then randomly selected between zero and CW. The user terminal would wait this amount of time before transmitting the F-RACH PDU for the next access attempt (step 540).

[0061] After waiting the randomly selected wait time, the user terminal again determines the F-RACH parameters for the current TDD frame by processing the BCH

message (step 522), randomly selects an F-RACH slot for transmission (step 524), and transmits the F-RACH PDU in the randomly selected F-RACH slot (step 526).

[0062] The F-RACH access procedure continues until either (1) the user terminal receives an acknowledgment from the access point or (2) the maximum number of permitted access attempts has been exceeded. For each subsequent access attempt, the amount of time to wait before transmitting the F-RACH PDU, the specific F-RACH slot to use for the F-RACH transmission, and the transmit power for the F-RACH PDU may be selected as described above.

B. S-RACH Procedure

[0063] In an embodiment, the S-RACH uses an Aloha random access scheme whereby user terminals transmit in randomly selected S-RACH slots to attempt to gain access to the system. Even though the user terminals attempt to transmit on specific S-RACH slots, the transmit timing for the transmissions on the S-RACH is not assumed to be RTD compensated. As a result, when the user terminals do not have good estimates of their RTDs, the behavior of the S-RACH is similar to that of an unslotted Aloha channel.

[0064] FIG. 6 shows a flow diagram of an embodiment of a process 430a performed by the user terminal for accessing the system using the S-RACH. Process 430a is an embodiment of the S-RACH access procedure performed in step 430 in FIG. 4.

[0065] Prior to the first transmission on the S-RACH, the user terminal initializes various parameters used for transmissions on the S-RACH (e.g., the number of access attempts, the initial transmit power, and so on) (step 612). The process then enters a loop 620.

[0066] For each transmission on the S-RACH, the user terminal processes the BCH to obtain pertinent parameters for the S-RACH for the current TDD frame, such as the number of S-RACH slots available and the start of the S-RACH segment (step 622). The user terminal next randomly selects one of the available S-RACH slots to transmit an S-RACH PDU (step 624). The S-RACH PDU includes an S-RACH message having the fields shown in Table 3. The RACH message includes either the assigned MAC ID, if the user terminal is registered with the system, or the registration MAC ID, otherwise. The user terminal then transmits the S-RACH PDU to the access point in the selected S-

RACH slot (step 626). If the user terminal knows the RTD, then it can adjust its transmit timing accordingly to account for the RTD.

[0067] The access point receives and processes the S-RACH PDU, recovers the S-RACH message, and checks the recovered message using the CRC value included in the message. The access point discards the S-RACH message if the CRC fails. If the CRC passes, then the access point obtains the MAC ID included in the recovered message and acknowledges receipt of the S-RACH PDU.

[0068] After transmitting the S-RACH PDU, the user terminal determines whether or not an acknowledgment has been received for the transmitted PDU (step 628). If the answer is yes, then the user terminal transitions to the Active state (step 630), and the process terminates. Otherwise, the user terminal assumes that the access point did not receive the S-RACH PDU and resumes the access procedure on the S-RACH.

[0069] For each subsequent access attempt, the user terminal first updates the S-RACH transmission parameters (e.g., increments the counter, adjusts the transmit power, and so on) (step 634). A determination is then made whether or not the maximum permitted number of access attempts on the S-RACH has been exceeded (step 636). If the answer is yes, then the user terminal would remain in the Access state (step 638), and the process terminates. Otherwise, the user terminal determines the amount of time to wait before transmitting the S-RACH PDU for the next access attempt. The wait time may be determined as described above for FIG. 5. The user terminal would wait this amount of time (step 640). After waiting the randomly selected wait time, the user terminal again determines the S-RACH parameters for the current TDD frame by processing the BCH message (step 622), randomly selects an S-RACH slot for transmission (step 624), and transmits the S-RACH PDU in the randomly selected S-RACH slot (step 626).

[0070] The S-RACH access procedure described above continues until either (1) the user terminal receives an acknowledgment from the access point or (2) the maximum number of permitted access attempts has been exceeded.

C. <u>RACH Acknowledgment</u>

[0071] In an embodiment, to acknowledge a correctly received F/S-RACH PDU, the access point sets a F/S-RACH Acknowledgment bit in the BCH message and transmits a RACH acknowledgement on the FCCH. Separate F-RACH and S-RACH Acknowledgment bits may be used for the F-RACH and S-RACH, respectively. There

may be a delay between the setting of the F/S-RACH Acknowledgment bit on the BCH and the sending of the RACH acknowledgment on the FCCH, which may be used to account for scheduling delay and so on. The F/S-RACH Acknowledgment bit prevents the user terminal from retrying and allows unsuccessful user terminals to retry quickly.

[0072] After the user terminal sends the F/S-RACH PDU, it monitors the BCH and FCCH to determine whether or not its PDU has been received by the access point. The user terminal monitors the BCH to determine whether or not the corresponding F/S-RACH Acknowledgment bit is set. If this bit is set, which indicates that an acknowledgment for this and/or some other user terminals may be sent on the FCCH, then the user terminal further processes the FCCH for the RACH acknowledgement. Otherwise, if this bit is not set, then the user terminal continues to monitor the BCH or resumes its access procedure.

[0073] The FCCH is used to carry acknowledgements for successful access attempts. Each RACH acknowledgement contains the MAC ID associated with the user terminal for which the acknowledgment is sent. A quick acknowledgement may be used to inform the user terminal that its access request has been received but is not associated with an assignment of FCH/RCH resources. An assignment-based acknowledgement is associated with an FCH/RCH assignment. If the user terminal receives a quick acknowledgement on the FCCH, it transitions to a Dormant state. If the user terminal receives an assignment-based acknowledgement, it obtains scheduling information sent along with the acknowledgment and begins using the FCH/RCH as assigned by the system.

[0074] If a user terminal is performing a registration, then it uses the registration MAC ID. For an unregistered user terminal, the RACH acknowledgment may direct the user terminal to initiate a registration procedure with the system. Via the registration procedure, the unique identity of the user terminal is ascertained based on, for example, an electronic serial number (ESN) that is unique for each user terminal in the system. The system would then assign a unique MAC ID to the user terminal (e.g., via a MAC ID Assignment Message sent on the FCH).

[0075] For the S-RACH, all unregistered user terminals use the same registration MAC ID to access the system. Thus, it is possible for multiple unregistered user terminals to coincidentally transmit in the same S-RACH slot. In this case, if the access point were able to detect a transmission on this S-RACH slot, then the system would

(unknowingly) initiate the registration procedure simultaneously with multiple user terminals. Via the registration procedure (e.g., through the use of CRC and the unique ESNs for these user terminals), the system will be able to resolve the collision. As one possible outcome, the system may not be able to correctly receive the transmissions from any of these user terminals because they interfere with one another, in which case the user terminals can restart the access procedure. Alternatively, the system may be able to correctly receive the transmission from the strongest user terminal, in which case the weaker user terminal(s) can restart the access procedure.

D. RTD Determination

[0076] The transmission from an unregistered user terminal may not be compensated for RTD and may arrive at the access point not aligned to an S-RACH slot boundary. As part of the access/registration procedure, the RTD is determined and provided to the user terminal for use for subsequent uplink transmissions. The RTD may be determined in various manners, some which are described below.

[0077] In a first scheme, the S-RACH slot duration is defined to be greater than the longest expected RTD for all user terminals in the system. For this scheme, each transmitted S-RACH PDU will be received starting in the same S-RACH slot for which the transmission was intended. There would then be no ambiguity as to which S-RACH slot was used to transmit the S-RACH PDU.

[0078] In a second scheme, the RTD is determined piecemeal by the access and registration procedures. For this scheme, the S-RACH slot duration may be defined to be less than the longest expected RTD. A transmitted S-RACH PDU may then be received zero, one, or multiple S-RACH slots later than the intended S-RACH slot. The RTD may be partitioned into two parts: (1) a first part for an integer number of S-RACH slots (the first part may be equal to 0, 1, 2, or some other value) and (2) a second part for a fractional portion of an S-RACH slot. The access point can determine the fractional portion based on the received S-RACH PDU. During registration, the transmit timing of the user terminal can be adjusted to compensate for the fractional portion so that the transmission from the user terminal arrives aligned to an S-RACH slot boundary. The first part may then be determined during the registration procedure and reported to the user terminal.

[0079] In a third scheme, the S-RACH message is defined to include a Slot ID field. This field carries the index of the specific S-RACH slot in which the S-RACH PDU was transmitted. The access point would then be able to determine the RTD for the user terminal based on the slot index included in the Slot ID field.

[0080] The Slot ID field may be implemented in various manners. In a first implementation, the S-RACH message duration is increased (e.g., from 2 to 3 OFDM symbols) while maintaining the same code rate. In a second implementation, the S-RACH message duration is maintained but the code rate is increased (e.g., from rate 1/4 to rate 1/2), which would allow for more information bits. In a third implementation, the S-RACH PDU duration is maintained (e.g., at 4 OFDM symbols) but the S-RACH message portion is lengthened (e.g., from 2 to 3 OFDM symbols) and the reference portion is shortened (e.g., from 2 down to 1 OFDM symbol).

[0081] Shortening the reference portion of the S-RACH PDU decreases the received signal quality for the reference, which would then increase the likelihood of not detecting an S-RACH transmission (i.e., higher missed detection probability). In this case, the detection threshold (which is used to indicate whether or not an S-RACH transmission is present) may be decreased to achieve the desired missed detection probability. The lower detection threshold increases the likelihood of declaring a received S-RACH transmission when none is present (i.e., higher false alarm probability). However, the CRC value included in each S-RACH message may be used to achieve an acceptable probability of false detection.

[0082] In a fourth scheme, the slot index is embedded in the CRC value for the S-RACH message. The data for an S-RACH message (e.g., the MAC ID, for the embodiment shown in Table 3) and the slot index may be provided to a CRC generator and used to generate a CRC value. The MAC ID and CRC value (but not the slot index) are then transmitted for the S-RACH message. At the access point, the received S-RACH message (e.g., the received MAC ID) and an expected slot index are used to generate a CRC value for the received message. The generated CRC value is then compared against the CRC value in the received S-RACH message. If the CRC passes, then the access point declares success and proceeds to process the message. If the CRC fails, then the access point declares failure and ignores the message.

E. F-RACH and S-RACH Transmissions

[0083] FIG. 7A shows an exemplary transmission on the S-RACH. The user terminal selects a specific S-RACH slot (e.g., slot 3) for transmission of an S-RACH PDU. However, if the S-RACH transmission is not RTD compensated, then the transmitted S-RACH PDU would not arrive time-aligned to the start of the selected S-RACH slot based on the access point timing. The access point is able to determine the RTD as described above.

[0084] FIG. 7B shows an exemplary transmission on the F-RACH. The user terminal selects a specific F-RACH slot (e.g., slot 5) for transmission of an F-RACH PDU. The F-RACH transmission is RTD compensated, and the transmitted F-RACH PDU arrives approximately time-aligned to the start of the selected F-RACH slot at the access point.

3. System

[0085] For simplicity, in the following description, the term "RACH" may refer to the F-RACH or S-RACH, or the RACH, depending on the context in which the term is used.

[0086] FIG. 8 shows a block diagram of an embodiment of an access point 110x and two user terminals 120x and 120y in system 100. User terminal 120x is equipped with a single antenna and user terminal 120y is equipped with N_{ut} antennas. In general, the access point and user terminals may each be equipped with any number of transmit/ receive antennas.

[0087] On the uplink, at each user terminal, a transmit (TX) data processor 810 receives traffic data from a data source 808 and signaling and other data (e.g., for RACH messages) from a controller 830. TX data processor 810 formats, codes, interleaves, and modulates the data to provide modulation symbols. If the user terminal is equipped with a single antenna, then these modulation symbols correspond to a stream of transmit symbols. If the user terminal is equipped with multiple antennas, then a TX spatial processor 820 receives and performs spatial processing on the modulation symbols to provide a stream of transmit symbols for each of the antennas. Each modulator (MOD) 822 receives and processes a respective transmit symbol stream to provide a corresponding uplink modulated signal, which is then transmitted from an associated antenna 824.

[0088] At access point 110x, N_{ap} antennas 852a through 852ap receive the transmitted uplink modulated signals from the user terminals, and each antenna provides a received signal to a respective demodulator (DEMOD) 854. Each demodulator 854 performs processing complementary to that performed at modulator 822 and provides received symbols. A receive (RX) spatial processor 856 then performs spatial processing on the received symbols from all demodulators 854a through 854ap to provide recovered symbols, which are estimates of the modulation symbols transmitted by the user terminals. An RX data processor 858 further processes (e.g., symbol demaps, deinterleaves, and decodes) the recovered symbols to provide decoded data (e.g., for recovered RACH messages), which may be provided to a data sink 860 for storage and/or a controller 870 for further processing. RX spatial processor 856 may also estimate and provide the received SNR for each user terminal, which may be used to determine whether the F-RACH or S-RACH should be used for system access.

[0089] The processing for the downlink may be the same or different from the processing for the uplink. Data from a data source 888 and signaling (e.g., RACH acknowledgment) from controller 870 and/or scheduler 880 are processed (e.g., coded, interleaved, and modulated) by a TX data processor 890 and further spatially processed by a TX spatial processor 892. The transmit symbols from TX spatial processor 892 are further processed by modulators 854a through 854ap to generate N_{ap} downlink modulated signals, which are then transmitted via antennas 852a through 852ap.

[0090] At each user terminal 120, the downlink modulated signals are received by antenna(s) 824, demodulated by demodulator(s) 822, and processed by an RX spatial processor 840 and an RX data processor 842 in a complementary manner to that performed at the access point. The decoded data for the downlink may be provided to a data sink 844 for storage and/or controller 830 for further processing.

[0091] Controllers 830 and 870 control the operation of various processing units at the user terminal and the access point, respectively. Memory units 832 and 872 store data and program codes used by controllers 830 and 870, respectively.

[0092] FIG. 9 shows a block diagram of an embodiment of a TX data processor 810a that can perform data processing for the F-RACH and S-RACH and which may be use for TX data processors 810x and 810y in FIG. 8.

[0093] Within TX data processor 810a, a CRC generator 912 receives the data for a RACH PDU. The RACH data includes just the MAC ID for the embodiments shown in Tables 2 and 3. CRC generator 912 generates a CRC value for the MAC ID if the S-RACH is used for system access. A framing unit 914 multiplexes the MAC ID and the CRC value (for an S-RACH PDU) to form the major portion of the RACH message, as shown in Tables 2 and 3. A scrambler 916 then scrambles the framed data to randomize the data.

[0094] An encoder 918 receives and multiplexes the scrambled data with tail bits, and further codes the multiplexed data and tail bits in accordance with a selected coding scheme to provide code bits. A repeat/puncture unit 920 then repeats or punctures (i.e., deletes) some of the code bits to obtain the desired code rate. An interleaver 922 next interleaves (i.e., reorders) the code bits based on a particular interleaving scheme. A symbol mapping unit 924 maps the interleaved data in accordance with a particular modulation scheme to provide modulation symbols. A multiplexer (MUX) 926 then receives and multiplexes the modulation symbols with pilot symbols to provide a stream of multiplexed symbols. Each of the units in TX data processor 810a is described in further detail below.

4. F-RACH and S-RACH Designs

[0095] As noted above, different designs are used for the F-RACH and S-RACH to facilitate rapid system access for registered user terminals and to minimize the amount of system resources needed to implement the RACH. Table 4 shows various parameters for exemplary designs of the F-RACH and S-RACH.

Table 4

Parameter	F-RACH	S-RACH	Units
PDU Length	1	4	OFDM symbols
CRC	No	Yes	
Code Rate	2/3	1/4	
Modulation Scheme	BPSK	BPSK	
Spectral Efficiency	0.67	0.25	bps/Hz

[0096] FIG. 10A shows a block diagram of an embodiment of CRC generator 912, which implements the following 8-bit generator polynomial:

$$g(x) = x^8 + x^7 + x^3 + x + 1 \quad . \qquad \text{Eq (1)}$$

Other generator polynomials may also be used for the CRC, and this is within the scope of the invention.

[0097] CRC generator 912 includes eight delay elements (D) 1012a through 1012h and five adders 1014a through 1014e that are coupled in series and implement the generator polynomial shown in equation (1). A switch 1016a provides the RACH data (e.g., the MAC ID) to the generator for the computation of the CRC value and N zeros to the generator when the CRC value is being read out, where N is the number of bits for the CRC and is equal to 8 for the generator polynomial shown in equation (1). For the embodiment described above wherein an m-bit slot index is embedded in the CRC, switch 1016a may be operated to provide the m-bit slot index followed by N - m zeros (instead of N zeros) when the CRC value is being read out. A switch 1016b provides the feedback for the generator during the computation of the CRC value and zeros to the generator when the CRC value is being read out. Adder 1014e provides the CRC value after all of the RACH data bits have been provided to the generator. For the embodiment described above, switches 1016a and 1016b are initially in the UP position for 10 bits (for the MAC ID) and then in the DOWN position for 8 bits (for the CRC value).

[0098] FIG. 10A also shows an embodiment of framing unit 914, which comprises a switch 1020 that selects the RACH data (or MAC ID) first and then the optional CRC value (if an S-RACH PDU is to be transmitted).

[0099] FIG. 10A further shows an embodiment of scrambler 916, which implements the following generator polynomial:

$$G(x) = x^7 + x^4 + x \quad . \qquad \text{Eq (2)}$$

Scrambler 916 includes seven delay elements 1032a through 1032g coupled in series. For each clock cycle, an adder 1034 performs modulo-2 addition of the two bits stored in delay elements 1032d and 1032g and provides a scrambling bit to delay element 1032a. The framed bits ($d_1\, d_2\, d_3$ ...) are provided to an adder 1036, which also

receives scrambling bits from adder 1034. Adder 1036 performs modulo-2 addition of each framed bit d_n with a corresponding scrambling bit to provide a scrambled bit q_n.

[00100] FIG. 10B shows a block diagram of an embodiment of encoder 918, which implements a rate 1/2, constraint length 7 ($K = 7$), binary convolutional code with generators of 133 and 171 (octal). Within encoder 918, a multiplexer 1040 receives and multiplexes the scrambled data and the tail bits. Encoder 918 further includes six delay elements 1042a through 1042f coupled in series. Four adders 1044a through 1044d are also coupled in series and used to implement the first generator (133). Similarly, four adders 1046a through 1046d are coupled in series and used to implement the second generator (171). The adders are further coupled to the delay elements in a manner to implement the two generators of 133 and 171, as shown in FIG. 10B. A multiplexer 1048 receives and multiplexes the two streams of code bits from the two generators into a single stream of code bits. For each input bit q_n, two code bits a_n and b_n are generated, which results in a code rate of 1/2.

[00101] FIG. 10B also shows an embodiment of repeat/puncture unit 920 that can be used to generate other code rates based on the base code rate of 1/2. Within unit 920, the rate 1/2 code bits from encoder 918 are provided to a repeating unit 1052 and a puncturing unit 1054. Repeating unit 1052 repeats each rate 1/2 code bit once to obtain an effective code rate of 1/4. Puncturing unit 1054 deletes some of the rate 1/2 code bits based on a specific puncturing pattern to provide the desired code rate. In an embodiment, the rate 2/3 for the F-RACH is achieved based on a puncturing pattern of "1110", which denotes that every fourth rate 1/2 code bits is deleted to obtain an effective code rate of 2/3.

[00102] Referring back to FIG. 9, interleaver 922 reorders the code bits for each RACH PDU to obtain frequency diversity (for both the S-RACH and F-RACH) and time diversity (for the S-RACH). For the embodiment shown in Table 2, an F-RACH PDU includes 16 data bits that are coded using rate 2/3 code to generate 24 code bits, which are transmitted on 24 data subbands in one OFDM symbol using BPSK.

[00103] Table 5 shows the subband interleaving for the F-RACH. For each F-RACH PDU, interleaver 922 initially assigns chip indices of 0 through 23 to the 24 code bits for the F-RACH PDU. Each code bit is then mapped to a specific data subband based on its chip index, as shown in Table 5. For example, the code bit with chip index 0 is

mapped to subband -24, the code bit with chip index 1 is mapped to subband -12, the code bit with chip index 2 is mapped to subband 2, and so on.

Table 5 - Pilot Symbols and Data Subband Interleaving for F-RACH

Sub-band Index	Pilot Symbol $p(k)$	Chip Index	Sub-band Index	Pilot Symbol $p(k)$	Chip Index	Sub-band Index	Pilot Symbol $p(k)$	Chip Index	Sub-band Index	Pilot Symbol $p(k)$	Chip Index
-32	0		-16		8	0	0		16		15
-31	0		-15	$1+j$		1	$-1-j$		17	$1-j$	
-30	0		-14		20	2		2	18		7
-29	0		-13	$1+j$		3	$-1-j$		19	$-1-j$	
-28	0		-12		1	4		14	20		19
-27	0		-11	$1+j$		5	$1+j$		21	$-1-j$	
-26	$-1+j$		-10		13	6		6	22		11
-25	$-1+j$		-9	$1-j$		7	$-1-j$		23	$-1-j$	
-24		0	-8		5	8		18	24		23
-23	$-1-j$		-7	$-1+j$		9	$1-j$		25	$-1+j$	
-22		12	-6		17	10		10	26	$1-j$	
-21	$-1-j$		-5	$-1-j$		11	$1+j$		27	0	
-20		4	-4		9	12		22	28	0	
-19	$-1-j$		-3	$-1+j$		13	$1-j$		29	0	
-18		16	-2		21	14		3	30	0	
-17	$1+j$		-1	$-1+j$		15	$-1+j$		31	0	

[00104] For the embodiment shown in Table 3, an S-RACH PDU includes 24 data bits that are coded and repeated to generate 96 code bits, which are transmitted on 48 data subbands in two OFDM symbols using BPSK. Table 6 shows the subband interleaving for the S-RACH. For each S-RACH PDU, interleaver 922 initially forms two groups of 48 code bits. Within each group, the 48 code bits are assigned chip indices of 0 through 47. Each code bit is then mapped to a specific data subband based on its chip index, as shown in Table 6. For example, the code bit with chip index 0 is mapped to subband -26, the code bit with chip index 1 is mapped to subband 1, the code bit with chip index 2 is mapped to subband -17, and so on.

Table 6 - Pilot Symbols and Data Subband Interleaving for S-RACH

Sub-band Index	Pilot Symbol $p(k)$	Chip Index	Sub-band Index	Pilot Symbol $p(k)$	Chip Index	Sub-band Index	Pilot Symbol $p(k)$	Chip Index	Sub-band Index	Pilot Symbol $p(k)$	Chip Index
-32	0		-16	-1+j	8	0	0		16	-1+j	39
-31	0		-15	1-j	14	1	1-j	1	17	-1+j	45
-30	0		-14	1+j	20	2	-1-j	7	18	1-j	5
-29	0		-13	1-j	26	3	-1-j	13	19	1+j	11
-28	0		-12	1-j	32	4	-1-j	19	20	-1+j	17
-27	0		-11	-1-j	38	5	-1+j	25	21	1+j	
-26	-1-j	0	-10	-1-j	44	6	1+j	31	22	-1+j	23
-25	-1+j	6	-9	1-j	4	7	-1-j		23	1+j	29
-24	-1+j	12	-8	-1-j	10	8	-1+j	37	24	-1+j	35
-23	-1+j	18	-7	1+j		9	-1-j	43	25	1-j	41
-22	1-j	24	-6	-1+j	16	10	-1-j	3	26	-1-j	47
-21	1-j		-5	-1-j	22	11	1+j	9	27	0	
-20	1+j	30	-4	-1+j	28	12	1-j	15	28	0	
-19	-1-j	36	-3	-1+j	34	13	-1+j	21	29	0	
-18	-1+j	42	-2	1-j	40	14	-1-j	27	30	0	
-17	1+j	2	-1	-1+j	46	15	1+j	33	31	0	

[00105] Symbol mapping unit 924 maps the interleaved bits to obtain modulation symbols. In an embodiment, BPSK is used for both the F-RACH and S-RACH. For BPSK, each interleaved code bit ("0" or "1") may be mapped to a respective modulation symbol, for example, as follows: $"0" \Rightarrow -1 + j0$ and $"1" \Rightarrow 1 + j0$. The modulation symbols from unit 924 are also referred to as data symbols.

[00106] Multiplexer 926 multiplexes the data symbols with pilot symbols for each RACH PDU. The multiplexing may be performed in various manners. Specific designs for the F-RACH and S-RACH are described below.

[00107] In an embodiment, for the F-RACH, the data symbols and pilot symbols are subband multiplexed. Each F-RACH PDU includes 28 pilot symbols multiplexed with

24 data symbols, as shown in Table 5. The subband multiplexing is such that each data symbol is flanked on both sides by pilot symbols. The pilot symbols may be used to estimate the channel responses for the data subbands (e.g., by averaging the channel responses for the pilot subbands on both sides of each data subband), which can be used for data demodulation.

[00108] In an embodiment, for the S-RACH, the data symbols and pilot symbols are time division multiplexed, as shown in FIG. 3B. Each S-RACH PDU includes a pilot OFDM symbol for each of the first two symbol periods and two data OFDM symbols for the next two symbol periods. In an embodiment, the pilot OFDM symbol comprises 52 QPSK modulation symbols (or pilot symbols) for 52 subbands and signal values of zero for the remaining 12 subbands, as shown in Table 6. The 52 pilot symbols are selected to have a minimum peak-to-average variation in a waveform generated based on these pilot symbols. This characteristic allows the pilot OFDM symbol to be transmitted at a higher power level without generating an excessive amount of distortion.

[00109] The multiplexing may also be performed for the S-RACH and F-RACH based on some other schemes, and this is within the scope of the invention. In any case, multiplexer 926 provides a sequence of multiplexed data and pilot symbols (denoted as $s(n)$) for each RACH PDU.

[00110] Each user terminal may be equipped with one or multiple antennas. For a user terminal with multiple antennas, the RACH PDU may be transmitted from the multiple antennas using beam-steering, beam-forming, transmit diversity, spatial multiplexing, and so on. For beam-steering, the RACH PDU is transmitted on a single spatial channel associated with the best performance (e.g., the highest received SNR). For transmit diversity, data for the RACH PDU is redundantly transmitted from multiple antennas and subbands to provide diversity. The beam-steering may be performed as described below.

[00111] On the uplink, a MIMO channel formed by N_{ut} terminal antennas and N_{ap} access point antennas may be characterized by a channel response matrix $\underline{\mathbf{H}}(k)$, for $k \in K$, where K represents the set of subbands of interest (e.g., $K = \{-26 \ldots 26\}$). Each matrix $\underline{\mathbf{H}}(k)$ includes $N_{ap}N_{ut}$ entries, where entry $h_{ij}(k)$, for $i \in \{1 \ldots N_{ap}\}$ and

$j \in \{1 \ldots N_{ut}\}$, is the coupling (i.e., complex gain) between the j-th user terminal antenna and the i-th access point antenna for the k-th subband.

[00112] The uplink channel response matrix $\underline{\mathbf{H}}(k)$ for each subband may be "diagonalized" (e.g., using eigenvalue decomposition or singular value decomposition) to obtain the eigenmodes for that subband. A singular value decomposition of the matrix $\underline{\mathbf{H}}(k)$ may be expressed as:

$$\underline{\mathbf{H}}(k) = \underline{\mathbf{U}}(k)\underline{\Sigma}(k)\underline{\mathbf{V}}^H(k) \quad \text{, for } k \in K \text{ ,} \qquad \text{Eq (3)}$$

where $\underline{\mathbf{U}}(k)$ is an $(N_{ap} \times N_{ap})$ unitary matrix of left eigenvectors of $\underline{\mathbf{H}}(k)$;

$\underline{\Sigma}(k)$ is an $(N_{ap} \times N_{ut})$ diagonal matrix of singular values of $\underline{\mathbf{H}}(k)$; and

$\underline{\mathbf{V}}(k)$ is an $(N_{ut} \times N_{ut})$ unitary matrix of right eigenvectors of $\underline{\mathbf{H}}(k)$.

[00113] The eigenvalue decomposition may be performed independently for the channel response matrix $\underline{\mathbf{H}}(k)$ for each of the subbands of interest to determine the eigenmodes for that subband. The singular values for each diagonal matrix $\underline{\Sigma}(k)$ may be ordered such that $\{\sigma_1(k) \geq \sigma_2(k) \geq \ldots \geq \sigma_{N_S}(k)\}$, where $\sigma_1(k)$ is the largest singular value and $\sigma_{N_S}(k)$ is the smallest singular value for the k-th subband. When the singular values for each diagonal matrix $\underline{\Sigma}(k)$ are ordered, the eigenvectors (or columns) of the associated matrix $\underline{\mathbf{V}}(k)$ are also ordered correspondingly. A "wideband" eigenmode may be defined as the set of same-order eigenmodes of all subbands after the ordering. The "principal" wideband eigenmode is the one associated with the largest singular value in each of the matrices $\underline{\Sigma}(k)$ after the ordering.

[00114] Beam-steering uses only the phase information from the eigenvectors $\underline{\mathbf{v}}_1(k)$, for $k \in K$, for the principal wideband eigenmode and normalizes each eigenvector such that all elements in the eigenvector have equal magnitudes. A normalized eigenvector $\tilde{\underline{\mathbf{v}}}(k)$ for the k-th subband may be expressed as:

$$\tilde{\underline{\mathbf{v}}}(k) = [Ae^{j\theta_1(k)} \;\; Ae^{j\theta_2(k)} \;\; \ldots \;\; Ae^{j\theta_{N_{ut}}(k)}]^T \quad , \qquad \text{Eq (4)}$$

where A is a constant (e.g., $A=1$); and

$\theta_i(k)$ is the phase for the k-th subband of the i-th user terminal antenna, which is given as:

$$\theta_i(k) = \angle v_{1,i}(k) = \tan^{-1}\left(\frac{\mathrm{Im}\{v_{1,i}(k)\}}{\mathrm{Re}\{v_{1,i}(k)\}}\right) , \qquad \text{Eq (5)}$$

where $\underline{\mathbf{v}}_1(k) = [v_{1,1}(k) \; v_{1,2}(k) \; \ldots \; v_{1,N_{ut}}(k)]^T$.

[00115] The spatial processing for beam-steering may then be expressed as:

$$\underline{\tilde{\mathbf{x}}}(k) = \underline{\tilde{\mathbf{v}}}(k)s(k) \quad , \text{for } k \in K , \qquad \text{Eq (6)}$$

where $s(k)$ is the data or pilot symbol to be transmitted on the k-th subband; and

$\underline{\tilde{\mathbf{x}}}(k)$ is the transmit vector for the k-th subband for beam-steering.

[00116] **FIG. 11** shows a block diagram of an embodiment of TX spatial processor 820y, which performs spatial processing for beam-steering. Within processor 820y, a demultiplexer 1112 receives and demultiplexes the interleaved data and pilot symbols $s(n)$ into K substreams (denoted as $s(1)$ through $s(k)$) for the K subbands used to transmit the data and pilot symbols. Each substream includes one symbol for an F-RACH PDU and four symbols for an S-RACH PDU. Each substream is provided to a respective TX subband beam-steering processor 1120, which performs the processing shown in equation (6) for one subband.

[00117] Within each TX subband beam-steering processor 1120, the substream of symbol(s) is provided to N_{ut} multipliers 1122a through 1122ut, which also respectively receive the N_{ut} elements $\tilde{v}_1(k)$ through $\tilde{v}_{N_{ut}}(k)$ of the normalized eigenvector $\underline{\tilde{\mathbf{v}}}(k)$. Each multiplier 1122 multiplies each received symbol with its normalized eigenvector value $\tilde{v}_i(k)$ to provide a corresponding transmit symbol. Multipliers 1122a through 1122ut provide N_{ut} transmit symbol substreams to buffers/multiplexers 1130a through 1130ut, respectively. Each buffer/multiplexer 1130 receives and multiplexes the transmit symbols from TX subband beam-steering processors 1120a through 1120k to provide a stream of transmit symbols, $x_i(n)$, for one antenna.

[00118] The processing for the beam-steering is described in further detail in the aforementioned provisional U.S. Patent Application Serial No. 60/421,309 and in U.S. Patent Application Serial No. 10/228,393, entitled "Beam-Steering and Beam-Forming for Wideband MIMO/MISO Systems," filed August 27, 2002, assigned to the assignee of the present application and incorporated herein by reference. RACH PDUs may also be transmitted by multiple-antenna user terminals using transmit diversity, beam-forming, or spatial multiplexing, which are also described in the aforementioned provisional U.S. Patent Application Serial No. 60/421,309.

[00119] FIG. 12A shows a block diagram of an embodiment of an OFDM modulator 822x, which may be used for each MOD 822 in FIG. 8. Within OFDM modulator 822x, an inverse fast Fourier transform (IFFT) unit 1212 receives a stream of transmit symbols, $x_i(n)$, and converts each sequence of 64 transmit symbols into its time-domain representation (which is referred to as a "transformed" symbol) using a 64-point inverse fast Fourier transform (where 64 corresponds to the total number of subbands). Each transformed symbol comprises 64 time-domain samples. For each transformed symbol, a cyclic prefix generator 1214 repeats a portion of the transformed symbol to form a corresponding OFDM symbol. In an embodiment, the cyclic prefix comprises 16 samples, and each OFDM symbol comprises 80 samples.

[00120] FIG. 12B illustrates an OFDM symbol. The OFDM symbol is composed of two parts: a cyclic prefix having a duration of, for example, 16 samples and a transformed symbol with a duration of 64 samples. The cyclic prefix is a copy of the last 16 samples (i.e., a cyclic continuation) of the transformed symbol and is inserted in front of the transformed symbol. The cyclic prefix ensures that the OFDM symbol retains its orthogonal property in the presence of multipath delay spread, thereby improving performance against deleterious path effects such as multipath and channel dispersion caused by frequency selective fading.

[00121] Cyclic prefix generator 1214 provides a stream of OFDM symbols to a transmitter unit (TMTR) 1216. Transmitter unit 1216 converts the OFDM symbol stream into one or more analog signals, and further amplifies, filters, and frequency upconverts the analog signal(s) to generate an uplink modulated signal suitable for transmission from an associated antenna.

5. Access Point Processing

[00122] For each TDD frame, the access point processes the F-RACH and S-RACH to detect for F/S-RACH PDUs sent by user terminals desiring to access the system. Because the F-RACH and S-RACH are associated with different designs and have different transmit timing requirements, different receiver processing techniques may be used by the access point to detect for F-RACH and S-RACH PDUs.

[00123] For the F-RACH, the transmit timing for the F-RACH PDUs are compensated for RTD and the received F-RACH PDUs are approximately aligned to F-RACH slot boundaries at the access point. A decision directed detector that operates in the frequency domain may be used to detect for F-RACH PDUs. In an embodiment, the detector processes all F-RACH slots in the F-RACH segment, one slot at a time. For each slot, the detector determines whether or not the desired signal energy for the OFDM symbol received in that slot is sufficiently high. If the answer is yes, then the OFDM symbol is further decoded to recover the F-RACH message.

[00124] For the S-RACH, the transmit timing for the S-RACH PDUs may not be compensated for RTD and the timing of the received S-RACH PDUs is not known. A sliding correlation detector that operates in the time domain may be used to detect for S-RACH PDUs. In an embodiment, the detector slides through the S-RACH segment, one sample period at a time. For each sample period, which corresponds to a hypothesis, the detector determines whether or not sufficient signal energy was received for the two pilot OFDM symbols of an S-RACH PDU hypothesized to have been received starting at that sample period. If the answer is yes, then the S-RACH PDU is further decoded to recover the S-RACH message.

[00125] Techniques for detecting and demodulating F-RACH and S-RACH transmissions are described in detail in the aforementioned U.S. Patent Application Serial No. 60/432,626.

[00126] For clarity, the random access techniques have been described for specific designs. Various modifications may be made to these designs, and this is within the scope of the invention. For example, it may be desirable to have more than two different types of RACH for random access. Moreover, the RACH data may be processed using other coding, interleaving, and modulation schemes.

[00127] The random access techniques may be used for various wireless multiple-access communication systems. One such system is a wireless multiple-access MIMO system described in the aforementioned provisional U.S. Patent Application Serial No. 60/421,309. In general, these systems may or may not employ OFDM, or may employ some other multi-carrier modulation scheme instead of OFDM, and may or may not utilize MIMO.

[00128] The random access techniques described herein may provide various advantages. First, the F-RACH allows certain user terminals (e.g., those that have registered with the system and can compensate for their RTDs) to quickly gain access to the system. This is especially desirable for packet data application, which is typically characterized by long periods of silence that are sporadically punctuated by bursts of traffic. Fast system access would then allow the user terminals to quickly obtain system resources for these sporadic data bursts. Second, the combination of the F-RACH and S-RACH is able to efficiently handle user terminals in various operating states and conditions (e.g., registered and unregistered user terminals, with high and low received SNRs, and so on).

[00129] The techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, software, or a combination thereof. For a hardware implementation, the elements used to facilitate random access at the user terminal and the access point may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, other electronic units designed to perform the functions described herein, or a combination thereof.

[00130] For a software implementation, the random access techniques may be implemented with modules (e.g., procedures, functions, and so on) that perform the functions described herein. The software codes may be stored in a memory unit (e.g., memory units 832 and 872 in FIG. 8) and executed by a processor (e.g., controllers 830 and 870). The memory unit may be implemented within the processor or external to the processor, in which case it can be communicatively coupled to the processor via various means as is known in the art.

[00131] Headings are included herein for reference and to aid in locating certain sections. These headings are not intended to limit the scope of the concepts described therein under, and these concepts may have applicability in other sections throughout the entire specification.

[00132] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

[00133] **WHAT IS CLAIMED IS:**